Lateral Mixing DRI: Turbulence-Resolving Simulations of Upper-Ocean Lateral Mixing

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LONG-TERM GOALS

This study contributes to our long-term efforts toward understanding:

- Mixed layer dynamics
- Processes that communicate atmospheric forcing to the ocean interior
- Frontal dynamics
- The interaction of finescale and submesoscale upper-ocean mixing at fronts.

OBJECTIVES

The focus of modeling in this study is to quantify relationships between surface fluxes of heat, energy and momentum, the available baroclinic potential energy, the resultant vertical mixing and geostrophic imbalance, and the ensuing dependence of lateral mixing at successively larger scales on atmospheric forcing.

APPROACH

Resolution of 3D large-eddy turbulence in boundary layers of depth 10m< H_{ML}<100m enables model-data comparisons against measurements of turbulence and dispersion. Such comparisons can critically assess the role of mixed layer dynamics and surface-driven vertical mixing in the cascades of baroclinic potential energy into submesoscale lateral mixing processes. Large Eddy Simulations (LES) have been done in close collaboration with E. A. D'Asaro and C. M. Lee, whose AESOP field experiments measured upper ocean mixing processes in the strong lateral density gradients of the Kuroshio and in a weaker front of the California Current off Monterey, during periods of varying wind and wave forcing (Fig. 1a,b). These simulations incorporate virtual Lagrangian Floats (D'Asaro) to provide a basis for interpreting these small-scale mixing measurements. A new line of inquiry has also been pursued under AESOP and Lateral Mixing DRI efforts in this year to examine relationships between small-scale dissipation measurements and the baroclinic environment in Gulf Stream

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measurements (Fig. 1c) obtained in the CLIMODE experiment by M.C. Gregg (also in AESOP) with post-doc R. Inoue. (R. Harcourt is not a member of the NSF CLIMODE experiment.)

WORK COMPLETED

Comparisons between LES model results and AESOP observations continued this year, in part as work under the Lateral Mixing DRI as well. Analysis of dissipation measurements from the wintertime Gulf Stream (Fig. 1c) complements the Monterey and Kuroshio results of AESOP with significantly different small-scale sensitivities to the baroclinic mixed layer environment. Results from the analysis of GS dissipation levels are described in the AESOP DRI report. Two manuscripts (Inoue et al., 2009a, 2009b, both in prep.) are approaching submission on this work, with the first complete and pending finalization of conclusions in the second. Both AESOP model-data comparisons and GS dissipation analysis efforts are important for framing Lateral Mixing DRIs in the strong frontal environment, for which the Gulf Stream off Cape Hatteras is now being seriously considered as a candidate experimental site. In addition, LES modeling has attempted to shed light on some submesoscale structures observed in capped-off mixed layers in the Florida current pilot LIDAR experiment, but so far these simulations were deemed unsuccessful due a lack of data on the hydrographic environment in this equipment test, and are not presented here. Current LES modeling efforts seek to relate surface forcing to deep pycnocline lateral mixing through breaking internal waves.

Significant progress has been made in accounting for the impact excess float buoyancy on Lagrangian float measurements. This problem is important in the context of Lateral Mixing observations because floats traversing density fronts under submesoscale lateral mixing can become significantly more or less dense than their environment, and although corrective ballasting is possible this capability is limited. A prescription for removing systematic errors due to float buoyancy from turbulence statistics of vertical velocity has been developed for a wide set of wind and wave-driven mixed layer cases (Harcourt & D'Asaro, *submitted*). This study also reflects ONR-sponsored work under the Typhoons and AESOP DRIs, with the results described below.

RESULTS

The effects of upward buoyancy on the accuracy with which Lagrangian floats can measure the Eulerian mean variance $\langle ww \rangle_E$ and skewness S_w^E of vertical fluid velocity w in the wind-driven upper ocean boundary layer is investigated using both simulated floats in large eddy simulation (LES) models and two float data sets. Nearly neutrally buoyant floats are repeatedly advected by the turbulent velocities across the boundary layer. Their vertical position Z is determined from pressure measurements; their W variance $\langle WW \rangle_F$ and skewness S_W^F are determined from the time series of float $W = dZ/dt$. If the float buoyancy is small, then the simulated floats measure the Eulerian velocity accurately, i.e., $\delta W^2 = \langle WW \rangle_F - \langle ww \rangle_E$ and $\delta S_W = S_W^F - S_w^E$ are small compared to $\langle ww \rangle_E$ and S_w^E, respectively. If the floats are buoyant and thus have an upward vertical velocity W_{bias} relative to the water, δW^2 and δS_W can become significant, as shown from modeled buoyant float statistics in Fig. 2.

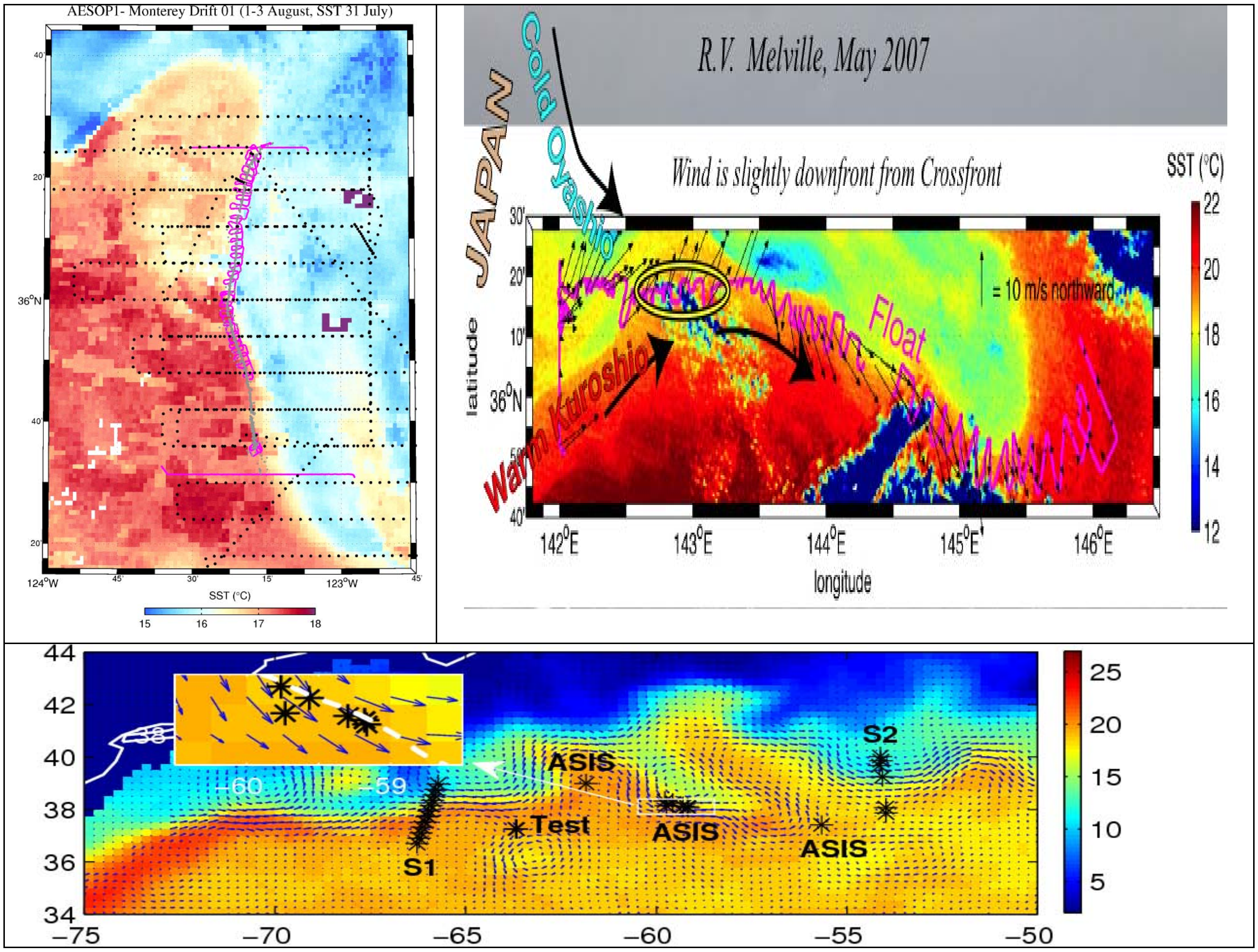

Figure 1: LES modeling has focused on two AESOP DRI field experiments, where rapid towed body surveys (magenta tracks) were used to measure the submesoscale environment of a Lagrangian float (gray tracks) deployed into a moderate strength front off Monterey (left) and a very strong frontal segment of the Kuroshio extension off Japan (above). Microstructure dissipation measurements from baroclinic mixed layers at CLIMODE wintertime Gulf Stream stations ('*' on SST map below) may be a Lateral Mixing DRI site.

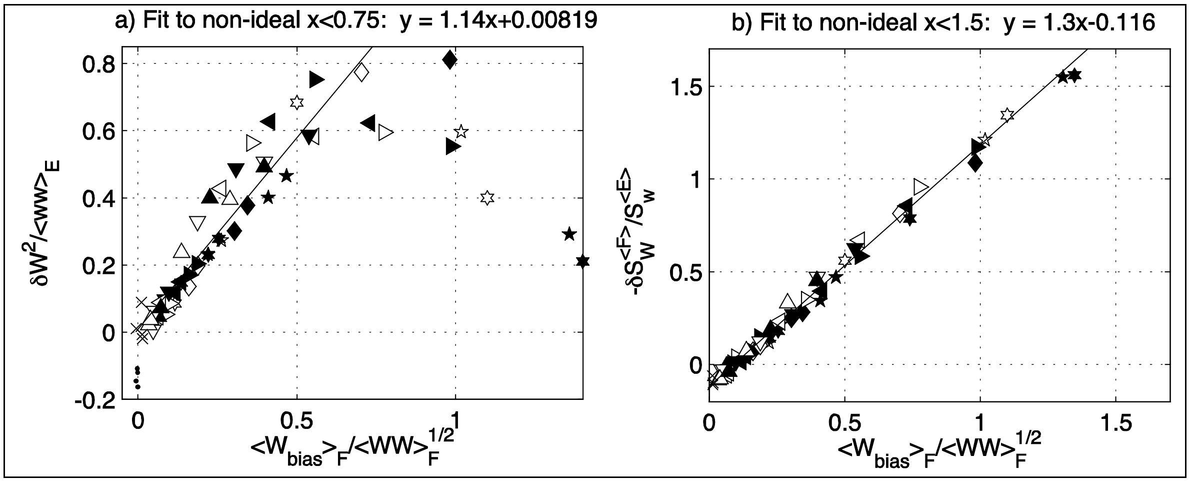

Fig. 2. ***Empirical relationships between nondimensional bias velocity*** $X = \langle W_{bias} \rangle_F / \langle W^2 \rangle_F^{1/2}$ ***and the relative errors a)*** $Y_1 = \langle WW \rangle_F / \langle ww \rangle_E - 1$ ***in VKE and b)*** $Y_2 = 1 - S_W^{\langle F \rangle} / S_w^{\langle E \rangle}$ ***in W-skewness. Solid lines are linear fits over*** $X < 0.75$ ***and*** $X < 1.5$***, respectively.***

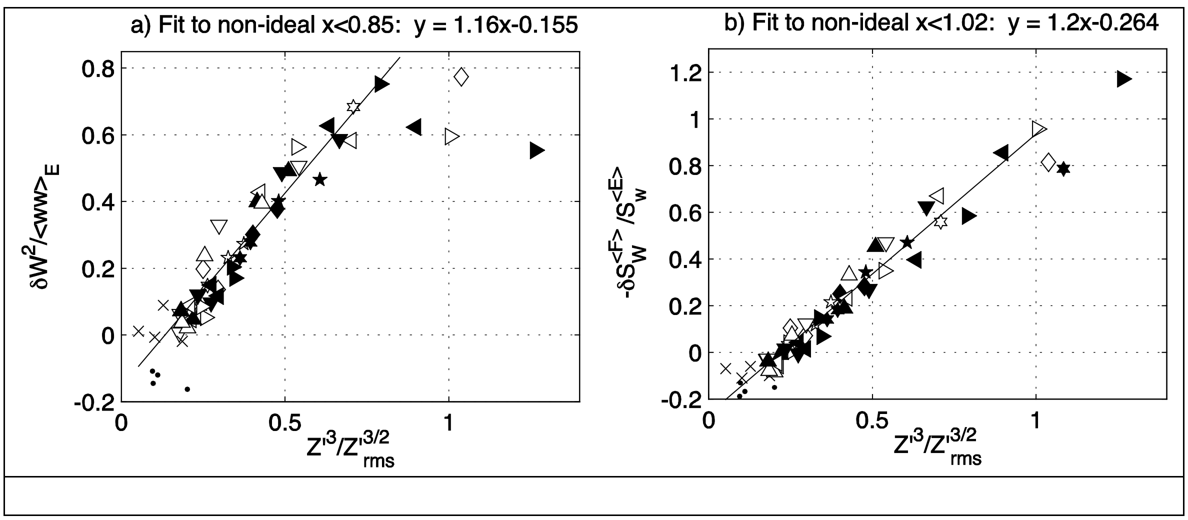

Fig. 3. ***Empirical relationships between the skewness*** $S_{Z'}^F$ ***of*** $Z' = Z - \langle Z \rangle_F$ ***and the relative errors a)*** $Y_1 = \delta W^2 / \langle W^2 \rangle_E$ ***and b)*** $Y_2 = -\delta S_W^{\langle F \rangle} / S_W^{\langle E \rangle}$ ***in VKE and skewness of bulk W moments. Solid lines are linear fits over*** $X < 0.85$ ***and*** $X < 1.02$***, respectively.***

Buoyancy causes Lagrangian floats to oversample both shallow depths and strong vertical velocities, leading to positive values of δW^2 and negative δS_W. The skewness S_Z^F of Z measures the degree to which shallow depths are oversampled. It is shown to be a good predictor of $W_{bias} / \langle WW \rangle_F^{1/2}$, $\delta W^2 / \langle WW \rangle_F$, and $\delta S_W / S_W^F$ over a wide range of float buoyancies and boundary layer forcings, as shown for buoyant model float data in Fig. 3.

Float data collected during two deployments confirm these results, but averaging times of several float-days are typically required to obtain stable statistics. In recent data from an experiment to study the North Atlantic Bloom, tightly controlled float buoyancy makes it possible to estimate excess buoyancy and rise velocity of the floats for comparison with the skewness $S_{Z'}^{F}$ of the depth distribution, shown in Fig. 4a. The observed relationship between the scaling of float VKE on friction velocity and variations in $S_{Z'}^{F}$ are shown for a wind-stress dominated N. Pacific mixed layer regime in Fig. 4b, supporting the LES-predicted trend at $S_{Z'}^{F}$<O(1), and suggesting observed VKE is elevated 10-20% by this effect. However, significant differences in the magnitude of this effect may occur between data sets from different ocean forcing regimes (e.g., greater buoyancy loss) and float designs (e.g., different automatic ballasting controls). Other measures of float buoyancy are also useful predictors. These results can be used to correct existing float measurements of $\langle ww \rangle_E$ for the effects of buoyancy and as a means to operationally assess and control float buoyancy.

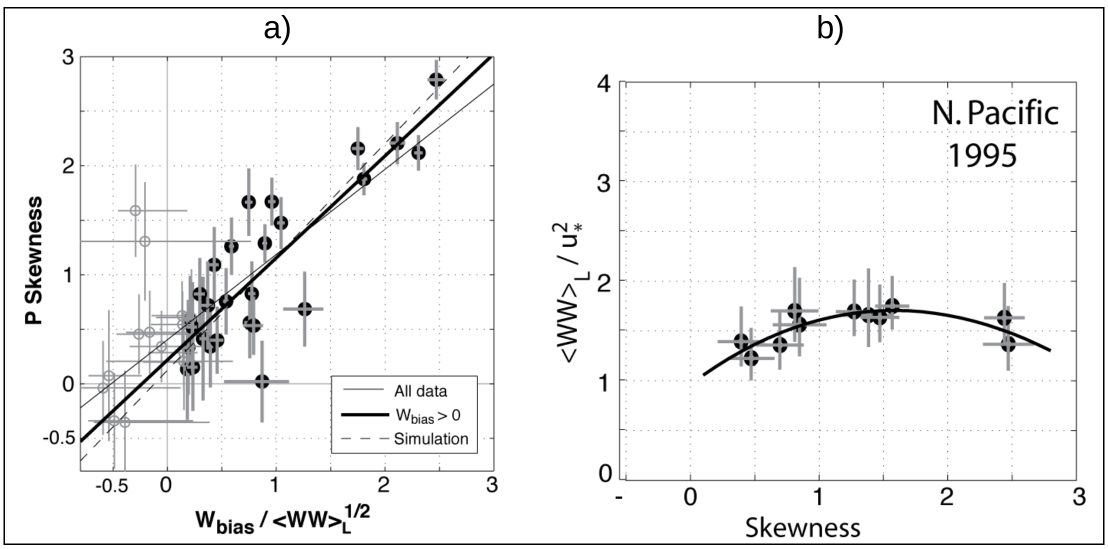

Fig. 4. a) Scatter plot of scaled W_{bias} and Z-skewness $S_{Z'}^{F}$ for North Atlantic Bloom float data. Heavy symbols show data for which W_{bias} > 0. Error bars represent ±1 g in W_{bias} and Guassian standard deviation in skewness. Lines are fits to all and heavy-only symbols and the simulation prediction. b) Vertical velocity variance as a function of Z-skewness $S_{Z'}^{F}$, for North Pacific 1995 data using averaging time of 240 ks. Heavy lines are cubic polynomial fits to the data.

The most straightforward relevance of float buoyancy diagnosis and corrective prescriptions in the context of the Lateral Mixing DRI is that it bears on the relationship of enhanced vertical mixing to upper ocean submesoscale dynamics. Enhanced levels of vertical mixing and TKE are predicted by both theories on the forward cascade of energy through submesoscales (e.g., Molemaker et al. 2008), and on the enhancements to buoyant TKE production by near-surface Ekman advection against density gradients (e.g., Thomas, 2005). These ideas have been encouraged recently by the observation of elevated TKE levels by Lagrangian Floats in the strongest fronts of the Kuroshio with down-front winds. These data continue to be examined not only for any effect of float buoyancy on elevating TKE

levels, but also for indications in the more sensitive W-skewness statistics for any distinct characteristics of slantwise mixing.

The same results may play a more subtle role in the identification of lateral heat and salinity fluxes from Lagrangian float data. In this study, the exact relationships between the Eulerian and Lagrangian vertical velocity budgets and the vertical PDF of depth were identified much more clearly than in prior work. Equivalent exact relationships exist for the Eulerian and Lagrangian budgets of tracer fluxes, and identifying lateral fluxes from their residual requires that very similar corrections need to be made to observed covariance vertical fluxes. These insights may also play a role in the interpretation of subsurface Lagrangian Float measurements in the context of the Lateral Mixing open ocean dye experiment.

IMPACT/APPLICATIONS

Lateral Mixing DRI results bear on the predictive skills of regional scale models with O(1-10) km resolution. At these scales the parameterizations of both vertical and lateral fluxes are not well understood or tested, especially in energetic frontal environments, or in subsurface environment where lateral mixing is driven by the relaxation of stratification anomalies produced by turbulent mixing events.

RELATED PROJECTS

One focus of the Lateral Mixing DRI is to continue a focus of the AESOP DRI to improve our understanding of mixed layer instabilties and associate lateral mixing process in a close collaboration between modeling and observations, and in particular on the combination of LES modeling and Lagrangian float observations. Typhoons DRI relies similarly on LES and LES-based models for the interpretation of Lagrangian float data, particularly where density changes along the float path due to lateral gradients can impact the relationship between Eulerian and Lagrangian turbulence statistics.

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